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Comparison of radiofrequency electromagnetic field exposure levels in different everyday microenvironments in an international context

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ABSTRACT

Background: The aim of this study was to quantify RF-EMF exposure applying a tested protocol of RF-EMF exposure measurements using portable devices with a high sampling rate in different microenvironments of Switzerland, Ethiopia, Nepal, South Africa, Australia and the United States of America.

Method: We used portable measurement devices for assessing RF-EMF exposure in 94 outdoor microenvironments and 18 public transport vehicles. The measurements were taken either by walking with a backpack with the devices at the height of the head and a distance of 20–30 cm from the body, or driving a car with the devices mounted on its roof, which was 170–180 cm above the ground. The measurements were taken for about 30 min while walking and about 15–20 min while driving in each microenvironment, with a sampling rate of once every 4 s (ExpoM-RF) and 5 s (EME Spy 201).

Results: Mean total RF-EMF exposure in various outdoor microenvironments varied between 0.23 V/m (non-central residential area in Switzerland) and 1.85 V/m (university area in Australia), and across modes of public transport between 0.32 V/m (bus in rural area in Switzerland) and 0.86 V/m (Auto rickshaw in urban area in Nepal). For most outdoor areas the major exposure contribution was from mobile phone base stations. Otherwise broadcasting was dominant. Uplink from mobile phone handsets was generally very small, except in Swiss trains and some Swiss buses.

Conclusions: This study demonstrates high RF-EMF variability between the 94 selected microenvironments from all over the world. Exposure levels tended to increase with increasing urbanity. In most microenvironments downlink from mobile phone base stations is the most relevant contributor.

1. Introduction

Knowledge of the radiofrequency electromagnetic field (RF-EMF) exposure of the population is useful for risk communication, assessment and management (Dürrenberger et al., 2014). However, little is known about differences in RF-EMF exposure of the general public in various microenvironments in different parts of the world. Recent studies have quantified RF-EMF levels in different microenvironments in Europe by collecting data during walking (Bhatt et al., 2016b; Bolte and Eikelboom, 2012; Joseph et al., 2010; Knafl et al., 2008; Sagar et al., 2016; Thuróczy et al., 2008; Urbinello et al., 2014a, 2014b; Urbinello and Röösli, 2013), by driving and using devices mounted on a car (Aerts

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et al., 2016; Bolte et al., 2016; Estenberg and Augustsson, 2014) or on a bicycle (Beekhuizen et al., 2013; Gonzalez-Rubio et al., 2016). Such microenvironmental measurements have several advantages. First, all sources can be measured, including wireless local area network (WLAN) hotspots and uplink from other people's mobile phones, which is not possible for simulation studies as data on these sources are not available for large scale modeling (Beekhuizen et al., 2015; Bürgi et al., 2010). Second, collecting data by a qualified technician enables one to adhere strictly to a measurement protocol and control data quality. This may not be the case in volunteer studies, where people may manipulate measurements by putting the measurement instrument close to sources or provide imprecise activity information during the data collection measurements (Bolte and Eikelboom, 2012; Frei et al., 2010). Further, measured uplink fields can be attributed to other people's mobile phones whereas this may not be possible in volunteer studies where the uplink is a mixture of emissions from volunteers' own and other people's mobile phones. Third, larger geographical areas can be covered than with spot measurements (Joseph et al., 2010; Urbinello et al., 2014a, 2014b) while still producing high reproducibility of measurements within the same microenvironment (Beekhuizen et al., 2013; Sagar et al., 2016). Nevertheless, propagation modeling may be able to capture larger areas in a more efficient manner if accurate data of all transmitters and building data are available (Aerts et al., 2013; Beekhuizen et al., 2015). Other challenges for measurements with portable devices are the sensitivity range, out-of- band response and body shielding, if carried directly on the body (Aminzadeh et al., 2018; Bolte, 2016).

Previous microenvironmental measurement studies used slightly different variants of measurement approaches and different kinds of measurement devices, which substantially hamper comparability (Sagar et al., 2017). For instance, some exposimeters with logarithmic detectors used in earlier studies were demonstrated to overestimate signals with bursts, such as uplink signals from mobile phones and WiFi appliances (Bolte, 2016). Also different strategies have been used to minimize body shielding which occurs if the body blocks the transmission between the source and the measurement device (Bolte, 2016). Previous measurements have been done mainly in Europe except for a few studies in Australia (Bhatt et al., 2016b, 2016a). Thus, the rest of the world remains basically untouched and information on the population exposures is missing. A comparative RF-EMF measurement using a standard protocol across several countries across the globe would be highly informative and enhance our knowledge of the population exposure on a global scale. Hence this study continues the effort of Sagar et al., 2016, where a measurement procedure was developed for Switzerland to monitor RF-EMF exposure in publicly-accessible microenvironments, with the aim to quantify the exposure levels in various microenvironments in Switzerland, Ethiopia, Nepal, South Africa, Australia and the United States of America.

2. Measurements and methods

2.1. Microenvironments selection

Table S1 (Supplementary material: Table S1) provides an overview of the selected microenvironments with a schedule of their measurements across all six countries. We selected 94 microenvironments from six countries across the globe following the tested protocol in Switzerland (Sagar et al., 2016). Our selected microenvironments represent urban and rural areas across the six countries and were selected based on available resources and time to measure the exposure. We focused on microenvironments where people spend part of their time. We included urban areas with high population density as previous studies found the highest RF-EMF exposure in such areas (Bhatt et al., 2016a, 2016b; Bolte et al., 2016; Bolte and Eikelboom, 2012; Estenberg and Augustsson, 2014; Frei et al., 2009; Joseph et al., 2010; Sagar et al., 2016; Urbinello et al., 2014a, 2014b, 2014c). Within each country, the set of matching microenvironments was chosen to provide greatest comparability across countries and included city centers, central residential, non-central residential, rural centers, rural residential, industrial, tourist and university areas (Bhatt et al., 2016a, 2016b; Joseph et al., 2010; Röösli et al., 2010; Sagar et al., 2016; Urbinello et al., 2014a, 2014b). The 94 selected microenvironments comprised 15 microenvironments from Switzerland (Europe), 18 from Ethiopia (Africa), 12 from Nepal (Asia), 17 from South Africa (Africa), 24 from Australia (Australia), and 8 from the United States of America (North America). In addition to these 94 microenvironments, 18 measurements were conducted in public transportation (train, tram, bus) including taxi and auto rickshaw during the journey of the study assistant to and from the measurement areas on the day of measurement.

2.2. Measuring devices

The RF-EMF exposure measurements in all the selected international microenvironments were measured using three different kinds of portable RF meter; the "ExpoM-RF v1", "ExpoM-RF v3" and "EME Spy 201". The two versions of ExpoM-RF (version 1: Expom and version 3: ExpoM-RF) were developed by Fields At Work; a spin-off company in Zurich, Switzerland (http://www.fieldsatwork.ch), and the EME Spy 201 was developed by Microwave Vision Group, France (http://www.mvg-world.com/en). The frequency bands of the ExpoM-RF cover the frequencies of most public RF-EMF emitting devices currently used in Switzerland, Ethiopia, Nepal, South Africa and Australia while the frequency bands of the EME Spy 201 cover the frequencies of most public RF-EMF emitting devices currently used in the United States of America (https://www.worldtimezone.com/gsm.html) (Supplementary material: Table S2). The upper limit of the ExpoM-RF dynamic range is 5 V/m (66 mW/m^2) for all frequency bands, and the lower limit of the dynamic range varies for different frequency bands; between 0.003 and 0.05 V/m (0.024–6.6 μW/m^2). The upper detection limit of the EME Spy 201 is 6 V/m (96 mW/m^2) and the lower detection limit is 0.005 V/m (0.066 μW/m^2), except for FM, TV-VHF and WiFi 5G, where it was 0.015 V/m (0.60 μW/m^2). Although both portable devices record values below the lower detection limit, we censored the values below half of the lower detection limit by replacing it with half of the lower detection limit. However, we did not find any value above 5 V/m; all the measured maximum values were below the upper detection limit of 5 V/m.

2.3. Measurement procedure

The RF-EMF exposure measurements were conducted either by walking (the pedestrian way) in Switzerland and Nepal or driving (outside from the driveway) a car with the device mounted on its roof in United States of America or a mixture of walking and driving in Ethiopia, South Africa, and Australia (Supplementary material: Table S1). Measurements by walking were conducted using a backpack with the devices at the height of the head (160–170 cm) and a distance of 20–30 cm from the body to ensure minimum shielding, and measurements by driving a car were conducted with the devices mounted on its roof, which was 170–180 cm above the ground. The measurements in public transportation including taxi and auto rickshaw were conducted with either carrying the backpack by the study assistant or keeping it vertical on the seat of the public transportation including taxi and auto rickshaw. Personal mobile phones were switched off while taking the measurements, and a mobile phone with a time stamp app was used in flight mode to record the start and end times of each measurement while walking or driving.

Each of the selected 94 microenvironments was measured twice between 10 March 2015 and 14 April 2017 (details see Supplementary material: Table S1). The RF-EMF exposure measurements using the ExpoM-RF were taken with a sampling rate of once every 4 s, and the EME Spy 201 with a sampling rate of once every 5 s. All measurements were taken during daylight between 9 am and 6 pm in the respective countries, except the United States of America where we also took night-time exposure measurements between 7 pm and 9 pm.

2.4. Statistical analyses

We considered five main groups of bands: downlink (exposure from mobile phone base stations), uplink (exposure from mobile phone handsets), broadcasting (exposure from FM radio and TV), other (WiFi 2G) and total RF-EMF (sum of downlink, uplink, broadcasting and other) for individual frequency bands used in the respective countries (Supplementary material: Table S3). We did not consider DECT cordless phone, WiMax (3.5 GHz) and WiFI 5G as they have been demonstrated to be affected by cross-talk (Bolte, 2016). Furthermore, DECT is not relevant in outdoor locations or public transport. At the time of the measurement WiFi 5G had not been fully introduced (Liu and Jiang, 2016), and most places we chose had only WiFi 2G. We descriptively analyzed the exposure levels including arithmetic mean values for all outdoor exposure including public transport. To assess reliability of the exposure values, we used Spearman measure of association across first and second measurements, and across day and night-time measurements. All of the analyses were conducted using statistical software R version 3.1.3 (https://www.rproject.org/) and measured values were converted to power flux density (mW/m^2). We further assessed variability across various outdoor microenvironments among all the selected countries.

3. Results

3.1. Characteristics of RF-EMF exposure levels in various microenvironments across six countries

Fig. 1 shows box plots for total RF-EMF, downlink, uplink and broadcasting exposure for eight different types of microenvironments across the six countries. The average exposure varied widely across the microenvironments. Fig. 2 summarizes mean RF-EMF exposure levels across countries for total RF-EMF, uplink, downlink, broadcasting and WiFi 2G, for each of the six different microenvironments. Mean total RF-EMF exposure for city centers was 0.48 V/m in Switzerland, 1.21 V/m in Ethiopia, 0.75 V/m in Nepal, 0.85 V/m in South Africa, 1.46 V/m in Australia and 1.24 V/m in the United States of America. Corresponding downlink exposure was 0.47 V/m, 0.94 V/m, 0.70 V/m, 0.81 V/m, 0.81 V/m and 1.22 V/m in Switzerland, Ethiopia, Nepal, South Africa, Australia and the United States, respectively. Exposure from uplink was negligible in outdoor microenvironments, but broadcasting was relevant in Addis Ababa (Ethiopia), Sydney and Canberra (Australia): 1.18 V/m, 1.12 V/m and 1.76 V/m, respectively. As a consequence, the highest total RF-EMF exposure levels measured in these microenvironments were 1.65 V/m, 1.80 V/m and 1.90 V/m, respectively (Fig. 3).

Mean total RF-EMF exposure for central residential areas was 0.35 V/m in Switzerland, 0.88 V/m in Ethiopia, 0.47 V/m in Nepal, 0.58 V/m in South Africa, 1.06 V/m in Australia and 1.44 V/m in the United States of America. Corresponding downlink exposure was 0.34 V/m, 0.67 V/m, 0.36 V/m, 0.55 V/m, 0.35 V/m and 1.39 V/m in Switzerland, Ethiopia, Nepal, South Africa, Australia and the United States, respectively. Mean total RF-EMF exposure for industrial areas was 0.69 V/m in Switzerland, 0.36 V/m in Ethiopia, 0.31 V/m in Nepal, 0.92 V/m in South Africa, 0.32 V/m in Australia and 1.14 V/m in the United States of America. Corresponding downlink exposure was 0.67 V/m, 0.35 V/m, 0.29 V/m, 0.91 V/m, 0.26 V/m and 1.11 V/m in Switzerland, Ethiopia, Nepal, South Africa, Australia and the United States, respectively. Mean total RF-EMF exposure for tourist areas was 0.68 V/m in Nepal, 0.60 V/m in South Africa, 1.39 V/m in Australia and 1.13 V/m in the United States of America. Corresponding downlink exposure was 0.66 V/m, 0.57 V/m, 0.39 V/m and 1.12 V/m in Nepal, South Africa, Australia and the United States, respectively (Table 1). In less urban areas, such as industrial, tourist, university or rural areas, exposure tended to be lower although exceptions were observed such as the industrial areas in Cape Town and Los Angeles (Fig. 3), the University area (2.51 V/m) in Canberra, the tourist area (2.01 V/m) in Sydney and the rural area (1.60 V/m) in Los Angeles (Fig. 2). We also looked at average frequency-specific exposure levels in all microenvironments and public transportation including taxi and auto rickshaw, across the six countries (Supplementary material: Table S4). For downlink exposure, the 900 MHz, 1800 MHz and 2100 MHz frequency bands were mostly used, except for the LTE Band 7 DL (2600 MHz in the United States of America).

In public transport in Switzerland and Nepal, mean total RF-EMF

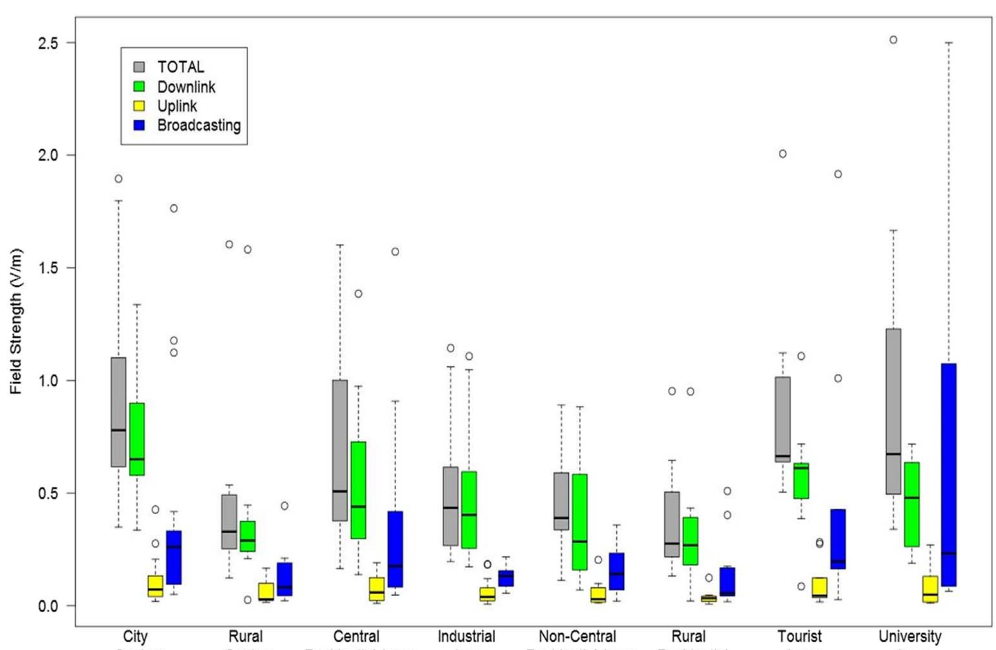

Fig. 1. Box plots showing exposure for total RF-EMF, downlink, uplink and broadcasting for eight different types of microenvironments.

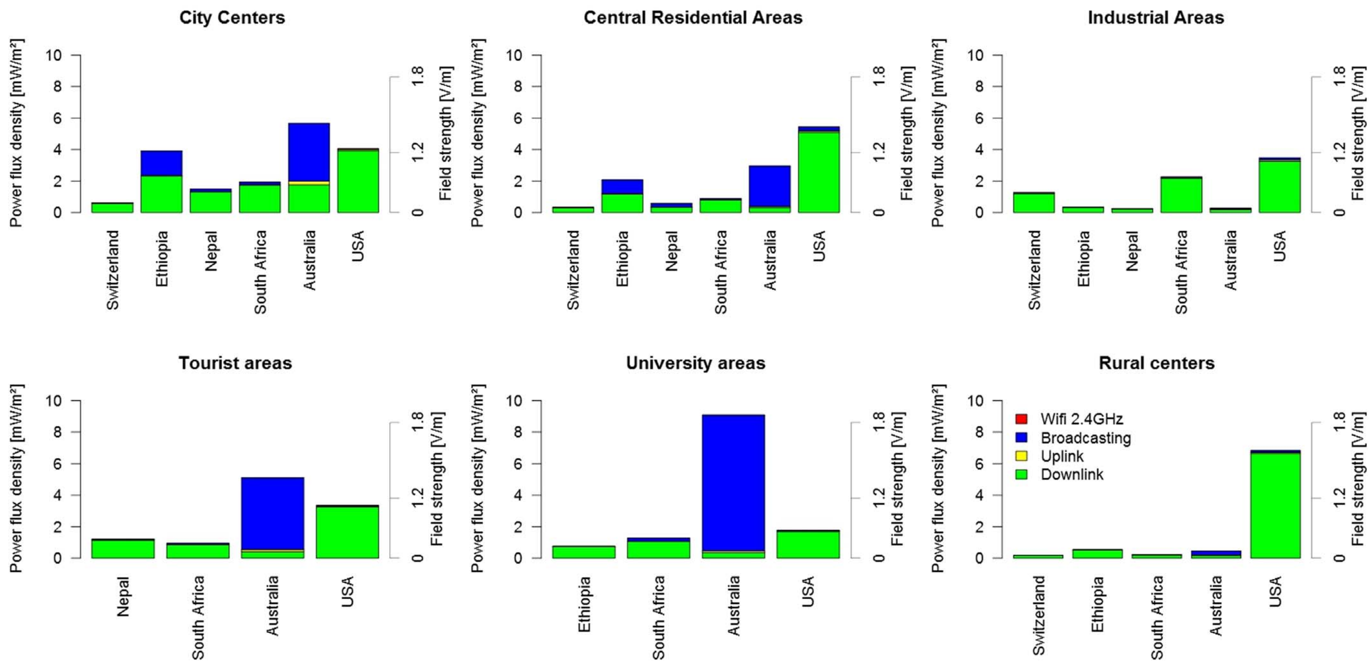

Fig. 2. Mean exposure levels are shown for six different microenvironments and across six countries, for total RF-EMF, uplink, downlink, broadcasting and WiFi 2G.

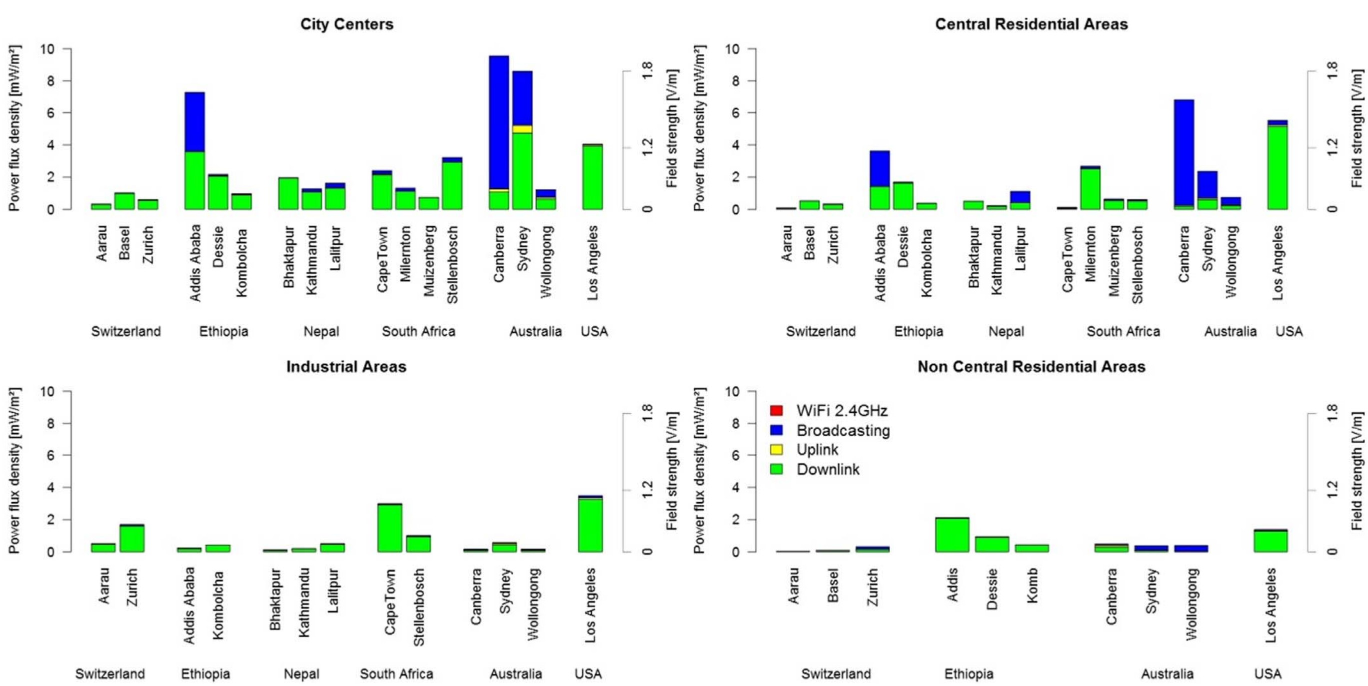

Fig. 3. Mean exposure levels are shown for four different microenvironments and across the various cities within the six countries separately, for total RF-EMF, uplink, downlink, broadcasting and WiFi 2G.

exposure was 0.57 V/m in trains (Switzerland), 0.38 V/m in trams (Switzerland), 0.37 V/m in buses (Switzerland), 0.86 V/m in auto rickshaw (Nepal), 0.60 V/m in taxi (Nepal), 0.50 V/m in police van (Nepal), 0.45 V/m in buses (Nepal), and 0.32 V/m in microbus (Nepal). In public transport the uplink exposure was often relevant. Corresponding uplink exposure was 0.47 V/m, 0.21 V/m, 0.22 V/m, 0.03 V/m, 0.12 V/m, 0.07 V/m, 0.24 V/m and 0.18 V/m, respectively (Table 1). The exposure from WiFi 2G was generally low, with the highest measured in trains (0.05 V/m) in Switzerland.

3.2. Comparison of RF-EMF exposure levels across different cities in six countries

Fig. 3 summarizes mean RF-EMF exposure levels across various cities for each type of microenvironment in the six countries. Mean total RF-EMF ranged between 0.35 and 1.90 V/m across the city centers. We found the highest mean total RF-EMF in the city centers of Canberra (1.90 V/m) and Sydney (1.80 V/m), followed by the city center in Addis Ababa (1.65 V/m). The main contributor to the mean total RF-EMF in these cities was broadcasting: 1.76 V/m in Canberra, 1.12 V/m in Sydney and 1.18 V/m in Addis Ababa. About 75% of the broadcasting

Table 1
Overall exposure levels in V/m across all selected microenvironments across all the six countries.

Microenvironments	Country	Number of microenvironments	Total	Downlink	Uplink	Broadcasting	Wifi 2.4GHz
City centers	Switzerland	3	0.48	0.47	0.06	0.09	0.02
	Ethiopia	3	1.21	0.94	0.10	0.77	0.02
	Nepal	3	0.75	0.70	0.07	0.25	0.02
	South Africa	4	0.85	0.81	0.08	0.25	0.03
	Australia	3	1.46	0.81	0.29	1.18	0.02
	United States of America	1	1.24	1.22	0.17	0.13	0.03
Central residential areas	Switzerland	3	0.35	0.34	0.04	0.07	0.02
	Ethiopia	4	0.88	0.67	0.08	0.57	0.01
	Nepal	3	0.47	0.36	0.04	0.30	0.01
	South Africa	4	0.58	0.55	0.05	0.17	0.02
	Australia	3	1.06	0.35	0.16	0.98	0.01
	United States of America	1	1.44	1.39	0.19	0.32	0.02
Industrial areas	Switzerland	2	0.69	0.67	0.06	0.14	0.02
	Ethiopia	2	0.36	0.35	0.01	0.08	0.01
	Nepal	3	0.31	0.29	0.04	0.08	0.01
	South Africa	2	0.92	0.91	0.02	0.16	0.03
	Australia	3	0.32	0.26	0.13	0.14	0.01
	United States of America	1	1.14	1.11	0.18	0.22	0.01
Tourist areas	Nepal	3	0.68	0.66	0.06	0.14	0.02
	South Africa	2	0.60	0.57	0.02	0.19	0.02
	Australia	3	1.39	0.39	0.23	1.31	0.01
	United States of America	1	1.13	1.12	0.12	0.13	0.03
University areas	Ethiopia	3	0.53	0.53	0.03	0.08	0.01
	South Africa	2	0.69	0.64	0.02	0.27	0.03
	Australia	3	1.85	0.37	0.20	1.80	0.01
	United States of America	1	0.82	0.80	0.07	0.14	0.01
Non central residential areas	Switzerland	3	0.23	0.18	0.02	0.14	0.01
	Ethiopia	3	0.57	0.57	0.02	0.08	0.01
	Australia	3	0.39	0.20	0.14	0.30	0.01
	United States of America	1	0.72	0.70	0.07	0.16	0.01
Rural centers	Switzerland	2	0.26	0.26	0.02	0.04	0.01
	Ethiopia	1	0.45	0.45	0.01	0.04	0.01
	South Africa	1	0.29	0.28	0.02	0.04	0.01
	Australia	3	0.42	0.26	0.10	0.31	0.01
	United States of America	1	1.60	1.58	0.17	0.21	0.01
Rural residential areas	Switzerland	2	0.22	0.21	0.02	0.05	0.00
	Ethiopia	1	0.29	0.28	0.01	0.06	0.01
	South Africa	1	0.24	0.23	0.01	0.04	0.01
	Australia	3	0.32	0.20	0.07	0.24	0.01
	United States of America	1	0.82	0.82	0.03	0.04	0.02
Shopping centers	Ethiopia	2	0.61	0.58	0.15	0.09	0.01
Informal area/Khalitsha	South Africa	1	0.91	0.85	0.02	0.32	0.03
Bus	Switzerland	3 rides	0.37	0.28	0.22	0.12	0.02
Train		4 rides	0.57	0.33	0.47	0.03	0.05
Tram		3 rides	0.38	0.3	0.21	0.08	0.03
Bus	Nepal	2 rides	0.45	0.34	0.24	0.20	0.01
Microbus		1 ride	0.32	0.27	0.18	0.02	0.01
Police van		1 ride	0.50	0.48	0.07	0.11	0.01
Taxi		3 rides	0.60	0.57	0.12	0.13	0.01
Auto rickshaw		1 ride	0.86	0.85	0.03	0.11	0.02

exposure in Canberra and Sydney corresponds to the FM Radio band, while in Addis Ababa both FM Radio and TV bands contributed equally. The lowest mean total RF-EMF exposure was found in the city center of Aarau (0.35 V/m), where approximately 90% of the exposure was from downlink band. Highest downlink exposure was 1.34 V/m, which was found in the city center of Sydney, and was closely followed by 1.22 V/m in Los Angeles.

Across central residential areas, mean total RF-EMF exposure ranged between 0.53 V/m and 1.60 V/m. The highest mean total RF-EMF exposure was found in the central residential area in Canberra (1.60 V/m), where most of the exposure was from broadcasting (1.57 V/m). Downlink exposure was found to be highest in the central residential area in Los Angeles (1.39 V/m), followed by 0.97 V/m in the central residential area in Milnerton. Mean total RF-EMF exposure in industrial areas varied between 0.10 V/m and 1.14 V/m. The highest mean total RF-EMF exposure was found in the industrial area in Los Angeles (1.14 V/m), where downlink comprised 1.11 V/m. The lowest exposure was 0.10 V/m in the industrial area in Bhaktapur, Nepal, where downlink comprised 0.09 V/m (Fig. 3). Similarly, across rural centers, mean total RF-EMF exposure ranged between 1.60 V/m in Los Angeles and 0.12 V/m in Sydney. Corresponding downlink exposure was 1.58 V/m in Los Angeles and 0.026 V/m in Sydney. Broadcasting also significantly contributed to the mean total RF-EMF: 0.12 V/m in Sydney and 0.21 V/m in Los Angeles.

Fig. 4 summarizes mean RF-EMF exposure levels across public transportation including taxi and auto rickshaw in Switzerland, Nepal and South Africa. Across various modes of public transport in Switzerland, South Africa and Australia, uplink exposure ranged between 0.03 V/m in auto rickshaw in Lalitpur and 0.56 V/m in trains in Zurich. Specifically, across train services, we found the highest uplink exposure to be 0.56 V/m in trains in Zurich and 0.44 V/m in trains in Seewen. Lowest uplink exposure was found to be 0.19 V/m in trains in Wollongong. Across tram services, we found the highest uplink exposures of 0.21 V/m in Munchenstein and Zurich. Across bus services, we found

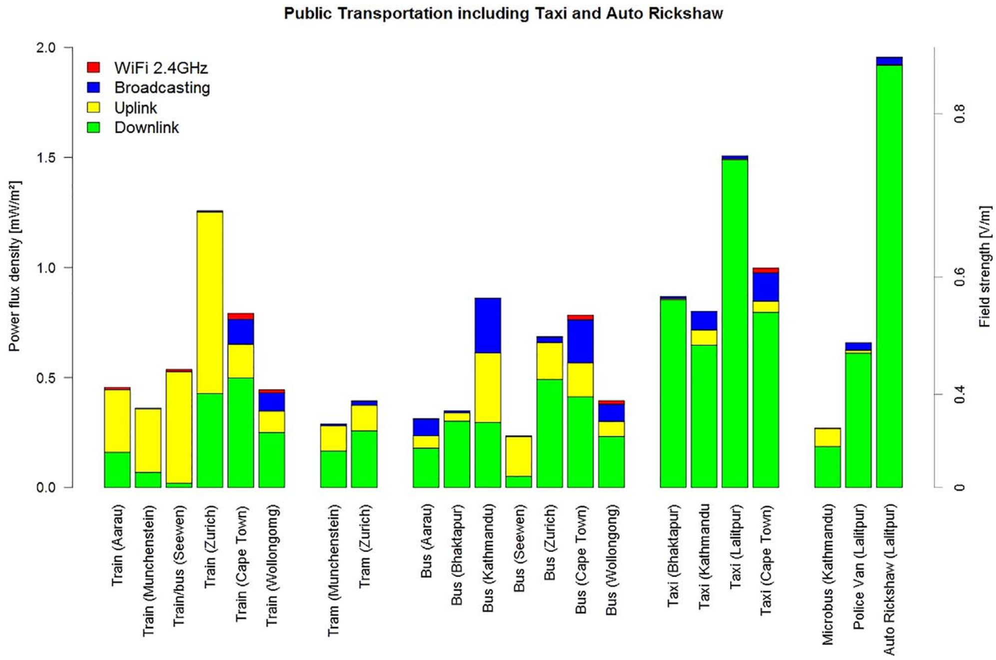

Fig. 4. Mean RF-EMF exposure levels across public transportation including taxi and auto rickshaw.

the highest uplink exposure in Kathmandu (0.34 V/m) and in Seewen (0.26 V/m), and the lowest uplink exposure in Bhaktapur (0.12 V/m). Similarly, across taxi services, the highest was 0.16 V/m in Kathmandu and the lowest uplink exposure was 0.05 V/m in Bhaktapur and Lalitpur.

3.3. Variability of RF-EMF exposure levels within same type of microenvironments

Table 2 summarizes the variability of total RF-EMF exposure levels across the same type of microenvironments of comparable outdoor microenvironments. The variability was calculated based on summary

Table 2
Variability of total RF-EMF exposure levels across the same type of microenvironments of comparable outdoor microenvironments.

Total RF-EMF		No. of microenvironment	Mean	Min	25perc	Median	75perc	Max	SD[a]	CV[b]
City centers	Switzerland	3	0.48	0.39	0.44	0.48	0.54	0.59	0.31	0.41
	Ethiopia	3	1.21	0.56	0.75	0.90	1.32	1.63	1.11	0.98
	Nepal	3	0.75	0.62	0.70	0.78	0.78	0.79	0.36	0.25
	South Africa	4	0.85	0.51	0.71	0.86	0.99	1.09	0.63	0.54
	Australia	3	1.46	0.71	1.31	1.72	2.13	2.48	1.68	0.88
Rural centers	Switzerland	2	0.26	0.22	0.24	0.27	0.29	0.31	0.18	0.45
	Australia	3	0.42	0.16	0.25	0.32	0.47	0.58	0.41	1.06
Rural residential areas	Switzerland	2	0.22	0.14	0.19	0.23	0.26	0.29	0.22	0.90
	Australia	3	0.32	0.19	0.22	0.26	0.52	0.69	0.49	1.28
Central residential areas	Switzerland	3	0.35	0.16	0.29	0.38	0.40	0.42	0.28	0.68
	Ethiopia	3	0.88	0.41	0.66	0.83	0.98	1.11	0.73	0.76
	Nepal	3	0.47	0.27	0.32	0.37	0.55	0.68	0.46	0.93
	South Africa	4	0.58	0.22	0.42	0.54	0.71	0.97	0.62	0.98
	Australia	3	1.06	0.60	0.84	1.03	1.81	2.35	1.67	1.21
Non central residential areas	Switzerland	3	0.23	0.12	0.13	0.14	0.25	0.32	0.22	1.06
	Ethiopia	3	0.57	0.37	0.47	0.55	0.74	0.88	0.57	0.81
	Australia	3	0.39	0.35	0.42	0.48	0.51	0.53	0.29	0.38
Industrial areas	Switzerland	2	0.69	0.42	0.53	0.63	0.71	0.78	0.55	0.77
	Ethiopia	2	0.36	0.32	0.34	0.36	0.37	0.39	0.18	0.25
	Nepal	3	0.31	0.15	0.22	0.27	0.37	0.45	0.31	0.95
	South Africa	2	0.92	0.63	0.76	0.87	0.96	1.05	0.70	0.66
	Australia	3	0.32	0.27	0.27	0.28	0.44	0.56	0.37	0.90
Tourist areas	Nepal	3	0.68	0.59	0.64	0.69	0.73	0.76	0.34	0.25
	South Africa	2	0.60	0.49	0.53	0.57	0.61	0.64	0.34	0.36
	Australia	3	1.39	0.80	1.12	1.37	1.90	2.31	1.56	0.93
University areas	Ethiopia	3	0.53	0.19	0.29	0.36	0.56	0.70	0.49	1.10
	South Africa	2	0.69	0.37	0.42	0.47	0.51	0.55	0.35	0.54
	Australia	3	1.85	0.87	1.41	1.80	2.45	2.97	2.03	0.97

Note: In the United States of America, we have only one microenvironment, hence we lack variability measures.
[a] Standard deviation
[b] CV = SD/mean.

statistics for the same type of microenvironments in the same country, and then variability was summarized for different microenvironments in each country as shown in Table 2. For total RF-EMF exposure, highest variability was found in rural residential areas in Australia (minimum 0.19 V/m, median 0.26 V/m, maximum 0.69 V/m, and coefficient of variation 1.28) and central residential areas in Australia (minimum 0.60 V/m, median 1.03 V/m, maximum 2.35 V/m, and coefficient of variation 1.10). Lowest variability across the micro-environments was observed for different city centers in Nepal (minimum 0.62 V/m, median 0.78 V/m maximum 0.79 V/m and coefficient of variation 0.25), industrial areas in Ethiopia (minimum 0.32 V/m, median 0.36 V/m, maximum 0.39 V/m, and coefficient of variation 0.25) and tourist areas in Nepal (minimum 0.59 V/m, median 0.69 V/m, maximum 0.76 V/m, and coefficient of variation 0.25).

For downlink exposure, highest variability was found in rural residential areas in Australia (minimum 0.02 V/m, median 0.09 V/m, maximum 0.41 V/m, and coefficient of variation 1.60), university areas in Ethiopia (minimum 0.14 V/m, median 0.35 V/m, maximum 0.70 V/m, and coefficient of variation 1.18), industrial areas in Australia (minimum 0.15 V/m, median 0.21 V/m, maximum 0.49 V/m, and coefficient of variation 1.16) and university areas in Australia (minimum 0.20 V/m, median 0.21 V/m, maximum 0.55 V/m, and coefficient of variation 1.16) (Supplementary material: Table S5).

3.4. Repeatability of RF-EMF exposure level

Each of the selected microenvironments was measured twice and the Spearman's measure of association between the first and second measurements per microenvironment was calculated. Spearman's measure of association for the first and second measurements, based on the arithmetic mean values of all outdoor microenvironments in Switzerland, was 0.97 for total RF-EMF, 0.98 for mobile phone downlink, 0.97 for uplink and 0.87 for broadcasting (Fig. 5). In Ethiopia, Spearman's measure of association was 0.71 for total RF-EMF, 0.49 for mobile phone downlink, 0.40 for uplink and 0.98 for broadcasting (Supplementary material: Fig. S1). In Nepal, Spearman's measure of association was 0.85 for total RF-EMF, 0.90 for mobile phone downlink, 0.25 for uplink and 0.90 for broadcasting (Supplementary material: Fig. S2). In South Africa, Spearman's measure of association was 0.77 for total RF-EMF, 0.72 for mobile phone downlink, 0.41 for uplink and 0.82 for broadcasting (Supplementary material: Fig. S3). Similarly, in Australia, Spearman's measure of association was 0.91 for total RF-EMF, 0.92 for mobile phone downlink, 0.89 for uplink and 0.88 for broadcasting (Supplementary material: Fig. S4). We also looked into potential relationships between day and night-time exposure in the United States of America. Spearman's measure of association between day and night time measurements was 0.62 for total RF-EMF, 0.67 for mobile phone downlink, 0.69 for uplink and 0.76 for broadcasting (Fig. 6).

4. Discussion

This multi-country study analyzed RF-EMF exposure levels in 94 microenvironments from six countries; Switzerland, Ethiopia, Nepal, South Africa, Australia and the United States of America. Each of the selected microenvironments was measured twice using ExpoM-RF (EME Spy 201 in the USA) following a protocol that was previously tested in

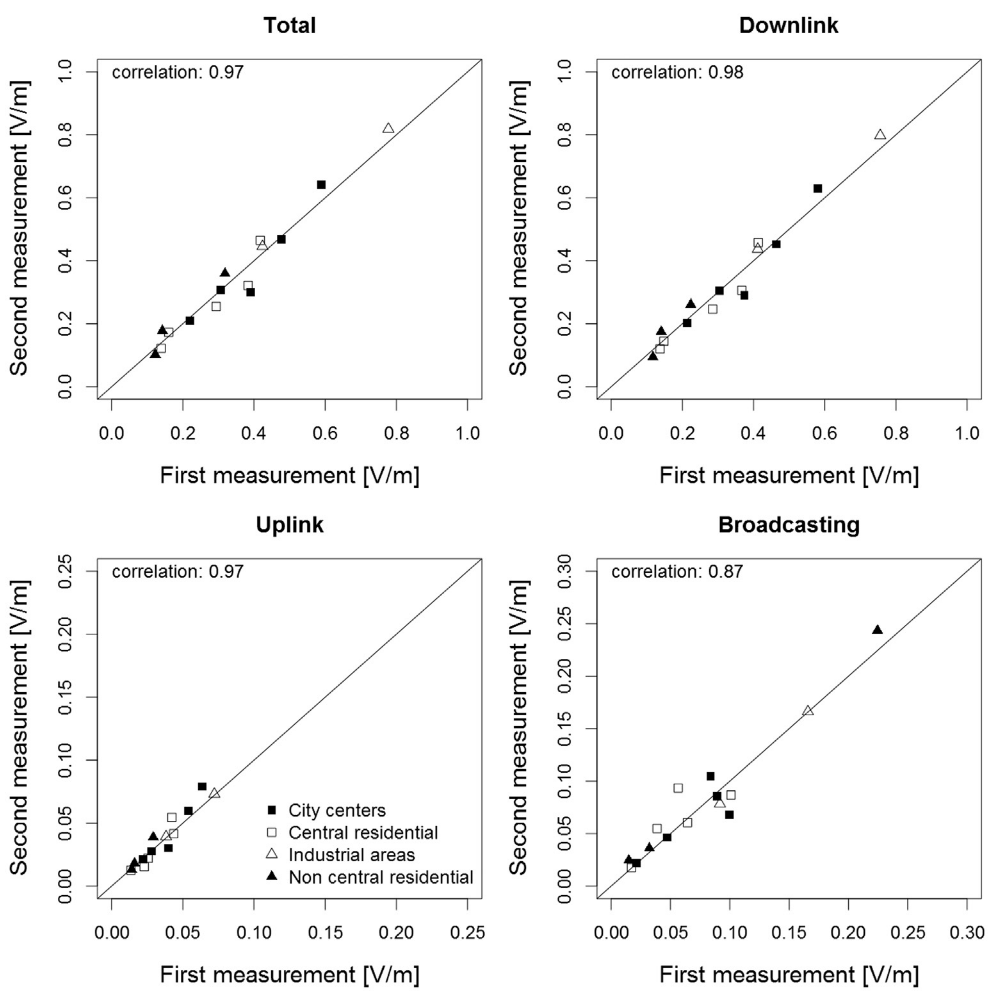

Fig. 5. Spearman's measure of association between the first and second measurement per microenvironment in Switzerland.

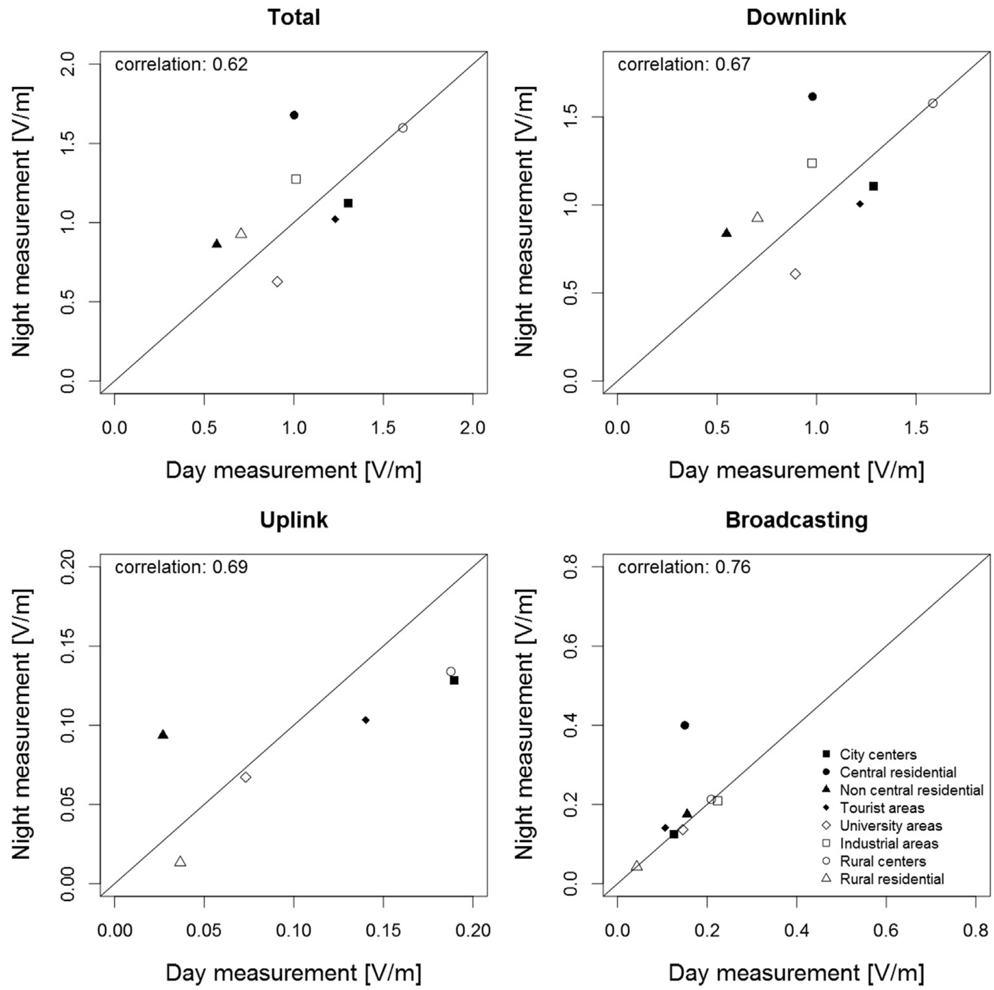

Fig. 6. Spearman's measure of association between day time and night-time measurements in the United States of America.

Switzerland (Sagar et al., 2016). Mean total RF-EMF exposure levels across various outdoor microenvironments in the selected countries varied widely, with the highest contribution from downlink in all microenvironments except some Australian and Ethiopian microenvironments where broadcasting contributed the most. In trains, uplink was the most relevant exposure source.

4.1. Comparison of exposure level with existing studies

Across 15 different microenvironments in Switzerland, mean total RF-EMF exposure varied between 0.22 V/m in rural residential areas and 0.69 V/m in industrial areas, which is in line with measurements conducted between 25 March and 11 July 2014, used to develop the current measurement protocol (Sagar et al., 2016). In previous international studies conducted in Europe, Swiss exposure levels were similar to measurements conducted in the Netherlands and in Belgium (Urbinello et al., 2014b). However, in the current study, Swiss exposure levels in urban areas were lower than in non-European cities. In particular, we found considerably higher exposure levels in Ethiopian, Australian and American cities. This is partly due to larger contributions of broadcasting, but downlink also tended to be higher in the non-European cities compared to Switzerland. One possible explanation for this discrepancy could be the denser building structure in Switzerland and Europe compared to the other cities, and the fact that Switzerland has implemented, in addition to the ICNIRP guidelines (ICNIRP, 1998), precautionary limits for areas where people live and work. As a consequence a denser network may be installed with lower emitted power. Further, RF-EMF from base stations may not propagate as easily into street canyons as it propagates in a more open building environment. Similarly, across public transportation we found the highest exposure from uplink in trains (0.47 V/m) in Switzerland, then bus (0.24 V/m) in Nepal, followed by bus (0.22 V/m) and tram (0.21 V/m) in Switzerland. The differences in the uplink exposure across public transportation in the two countries could be mainly due to the fact that Switzerland is technologically more advanced than Nepal where fewer people traveling on public transportation use smartphones. The uplink exposure levels in this study are lower than previous measurements obtained in Switzerland (Sagar et al., 2016) and in Basel (0.97 V/m), Ghent (0.83 V/m) and Brussels (1.05 V/m) (Urbinello et al., 2014a).

Our study found that mobile phone base stations (downlink) generally contributed the most to the total RF-EMF in outdoor microenvironments, which is in line with previous studies conducted in Europe (Sagar et al., 2016; Urbinello et al., 2014c), except for some Australian and Ethiopian microenvironments where broadcasting contributed the most to the total RF-EMF exposure values. The broadcasting values from our study were slightly higher (1.18 V/m) in city centers in Australia than were measured (0.73 V/m) by Bhatt et al. (2016b). This difference could be because we measured three large cities (Sydney, Canberra and Wollongong), whereas Bhatt et al. (2016b) measured one large city.

4.2. Strengths and limitations

This multi-country non-ionizing radiation monitoring study used a common protocol (Sagar et al., 2016) in order to provide a direct comparison of RF-EMF exposures across various microenvironments in six countries: Switzerland, Ethiopia, Nepal, South Africa, Australia and the United States of America. This is the first study to globally apply the same protocol and devices (with the exception of the USA, which used different frequency bands). Nevertheless, some differences in methods were applied between countries (due to security or practicality reasons), which may hamper comparability. We conducted the measurement by driving, walking, or both. When driving, a portable exposimeter was mounted on the roof of a car and measurements taken for about 15–20 min. In this case, RF-EMF may be reflected from the roof and measurements may somewhat overestimate the true exposure. While walking, the measurement was conducted using a backpack with the exposimeter on its top at a distance of about 20–30 cm away from the body in order to minimize body shielding. In previous studies, keeping the exposimeters close, within 10–50 mm of the body, produced underestimation of the incident field strength by about 10–50% for some frequency bands (Blas et al., 2007; Bolte and Eikelboom, 2012; Iskra et al., 2010; Knafl et al., 2008; Neubauer et al., 2007; Radon et al., 2006). To assess cross validation of the body shielding and bias, we repeated measurements in the Cape Town city center by both driving a car with the device mounted on its roof and by walking with a backpack with the device on the top. The total RF-EMF exposure levels changed slightly 0.98 V/m while driving and 0.92 V/m while walking, however the difference was mainly due to an increase in uplink and broadcasting exposure levels, which is in line with a previous study (Bolte et al., 2016).

All of the measurements were conducted by the same person to ensure consistent implementation of the sampling and measurement procedures. This approach did not enable us to conduct the measurements at the same time point. Rather our measurements were taken over a period of 2 years (from March 2015 to April 2017). Thus, if exposure on a global scale would have increased during this time period, this would bias the comparison between microenvironments. Little research on time trends has been published so far. Whereas Urbinello et al. found an increase of 57.1% in the outdoor Basel area between April 2011 and March 2012 (Urbinello et al., 2014a), no indication of a time trend was seen in other studies (Rowley and Joyner, 2012; Sagar et al., 2017). This suggests that any potential time trend during the study period is likely to be small relative to the large variability observed between areas.

Conducting measurements by a trained researcher brings the advantage that the researcher's mobile phone could be turned off; thus measured uplink can be unambiguously attributed to exposure from other people's mobile phones, which may not be the case in volunteer studies (Frei et al., 2009; Viel et al., 2009).

On the other hand, this study has some drawbacks. Our study selected only a few microenvironments for repeated measurements. A different selection of microenvironments in one country might have produced different results; thus, our data cannot be taken as representative of the corresponding countries. To achieve this would require more environments selected for measurements. It is striking that measurements were highly reproducible within the same area. This suggests that future studies do not need to invest too much time into assessing repeatability, and could profitably use the saved resource to cover more microenvironments. We used two different devices (ExpoM-RF and EME Spy 201) that were relevant to the frequency bands in the selected six countries, and this might have influenced the total RF-EMF exposure levels since the frequency bands were different for both devices. Hence, it would be useful in future research to use a device with modified frequency bands that are applicable to all microenvironments across all of the countries assessed.

5. Conclusion

Overall, mean total RF-EMF exposure levels in all countries are substantially below ICNIRP guideline limits for the general population (ICNIRP, 1998). This study demonstrates high RF-EMF variability between selected microenvironments, and that exposure tends to increase with increasing urban level. Most exposure comes from downlink in outdoor environments, except in Australia where broadcasting was the most important contributor. Uplink is in general not relevant in outdoor environments; however, it is an important source in public transportation and exhibits large variability. WLAN was negligible in all measured microenvironments. This study demonstrates the benefit of using a common protocol to monitor RF-EMF, and, given the substantial number of measurements, provides strong conclusions regarding spatial and temporal exposure trends on a global scale.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgement

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2018.02.036.

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